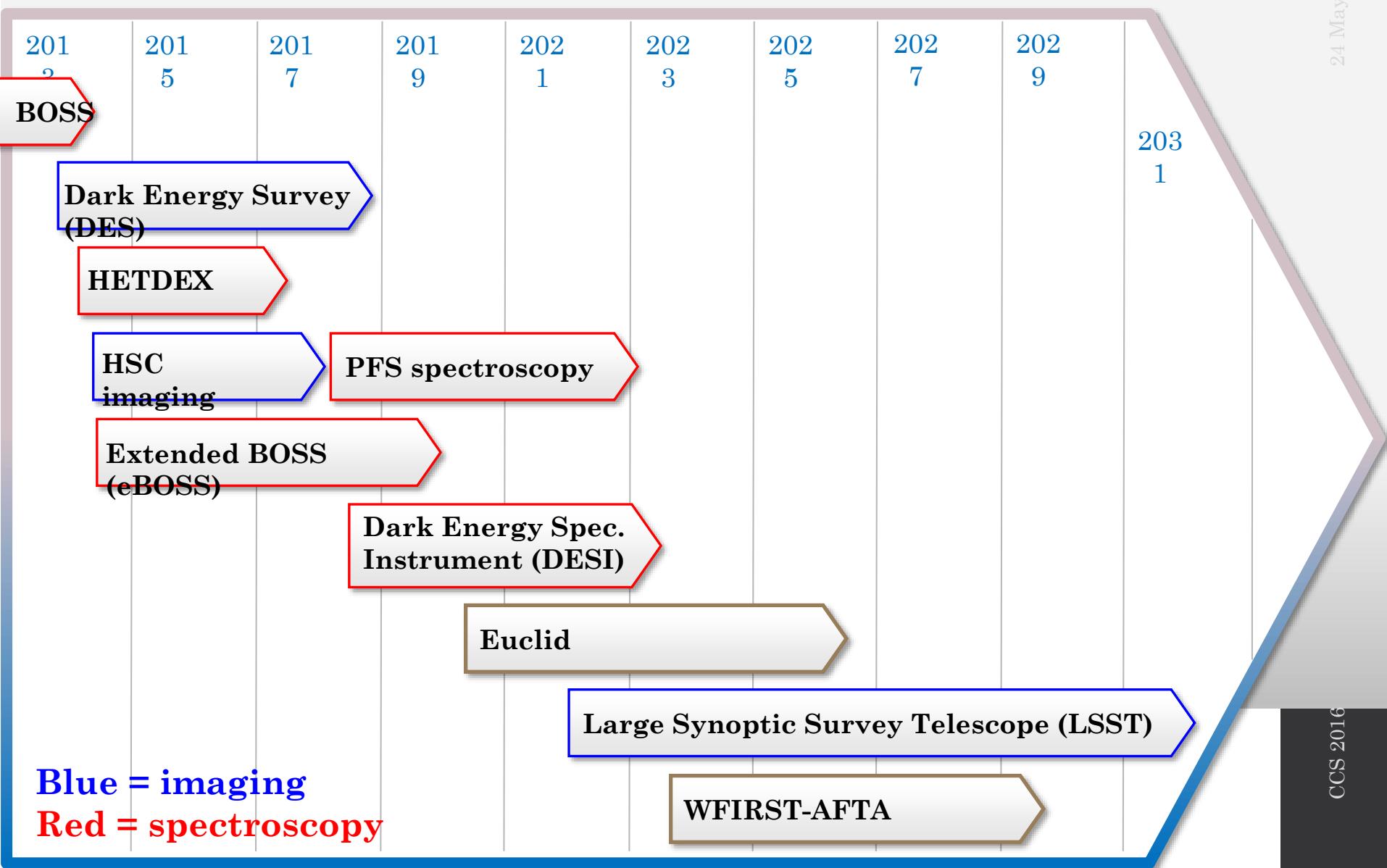


# (A) Spectroscopic survey(s) and opportunities for cross-correlations

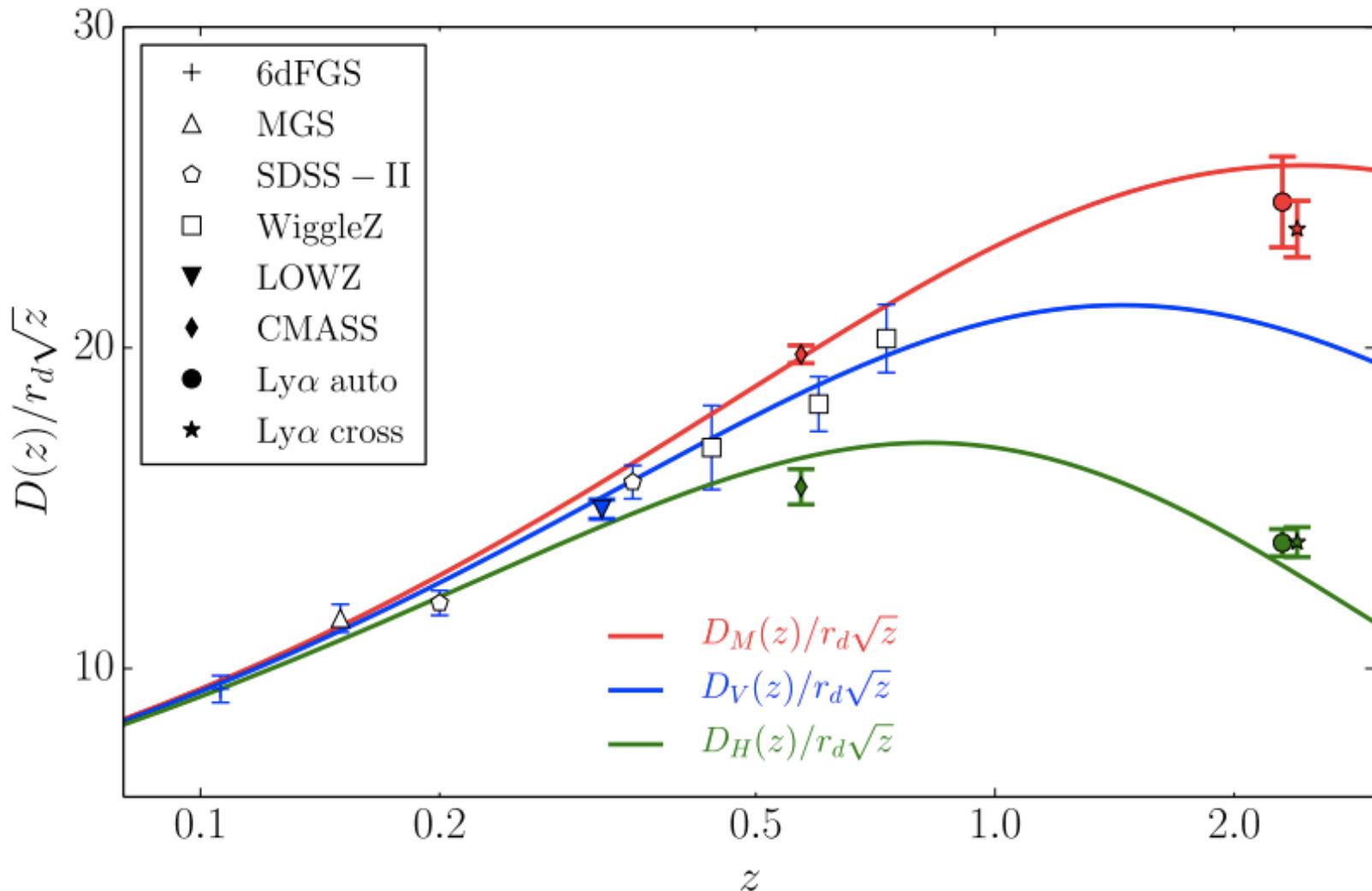
The BOSS and DESI clustering groups

# Dark Energy Experiments: 2013 - 2031

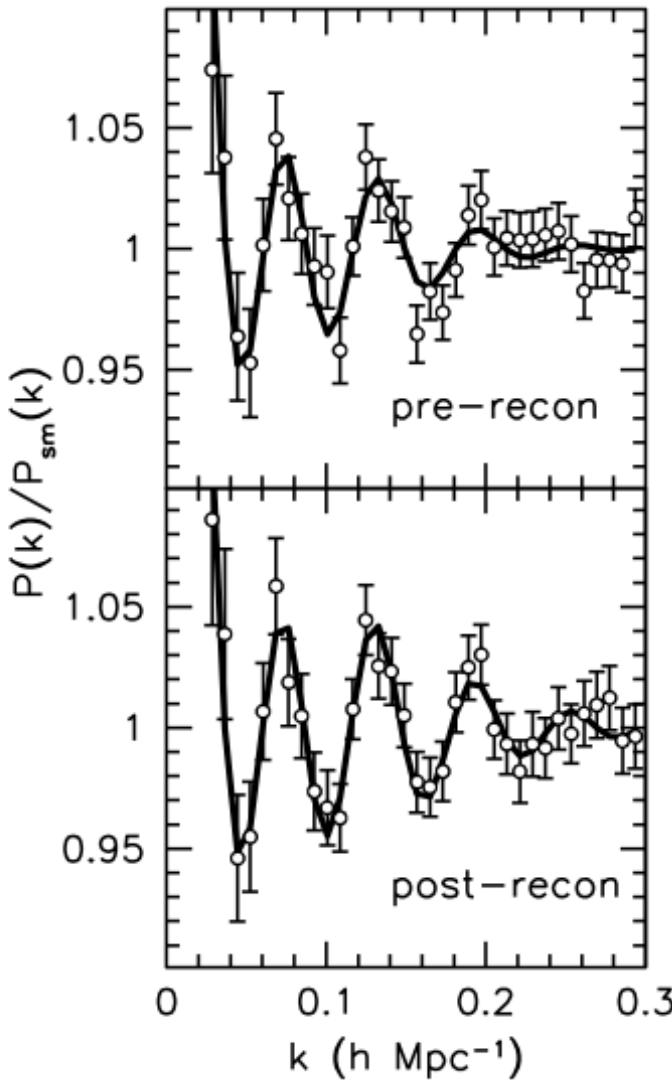
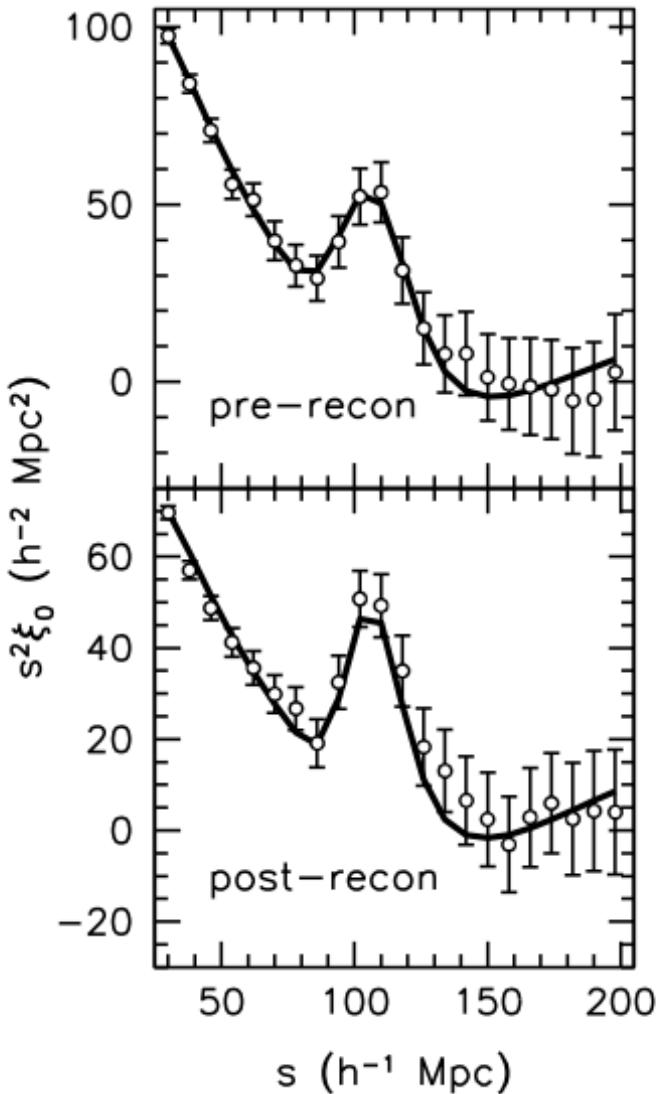


... and many others (JPAS, PAU, KIDS, CHIME,...) Weinberg et al, Snowmass 2013

# A BAO Hubble diagram



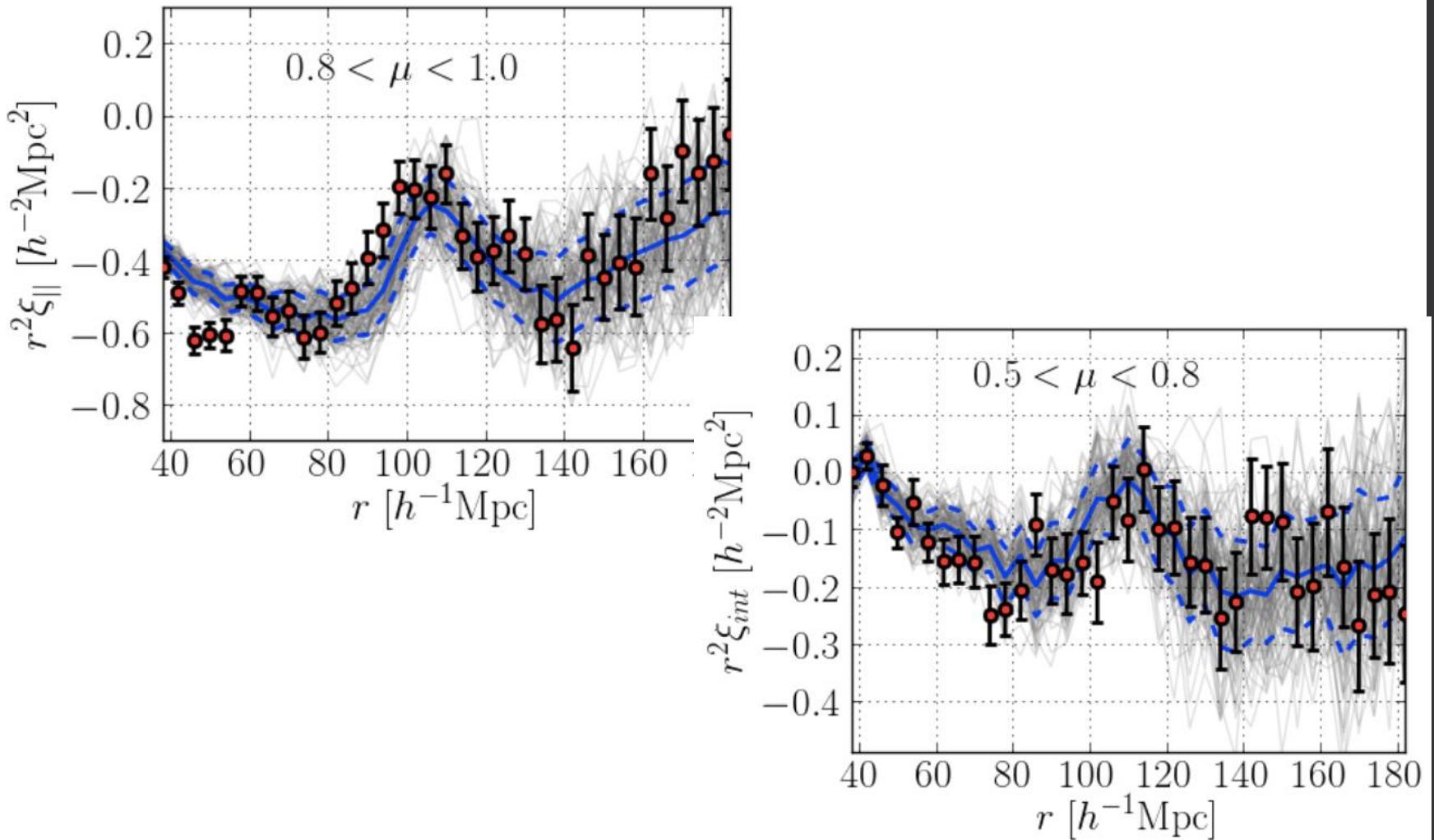
# The BAO feature in BOSS galaxies



8 sigma  
detection

$\sim 1\%$   
distance at  
 $z \sim 0.55$ ,  
 $\sim 2\%$  at  
 $z \sim 0.35$

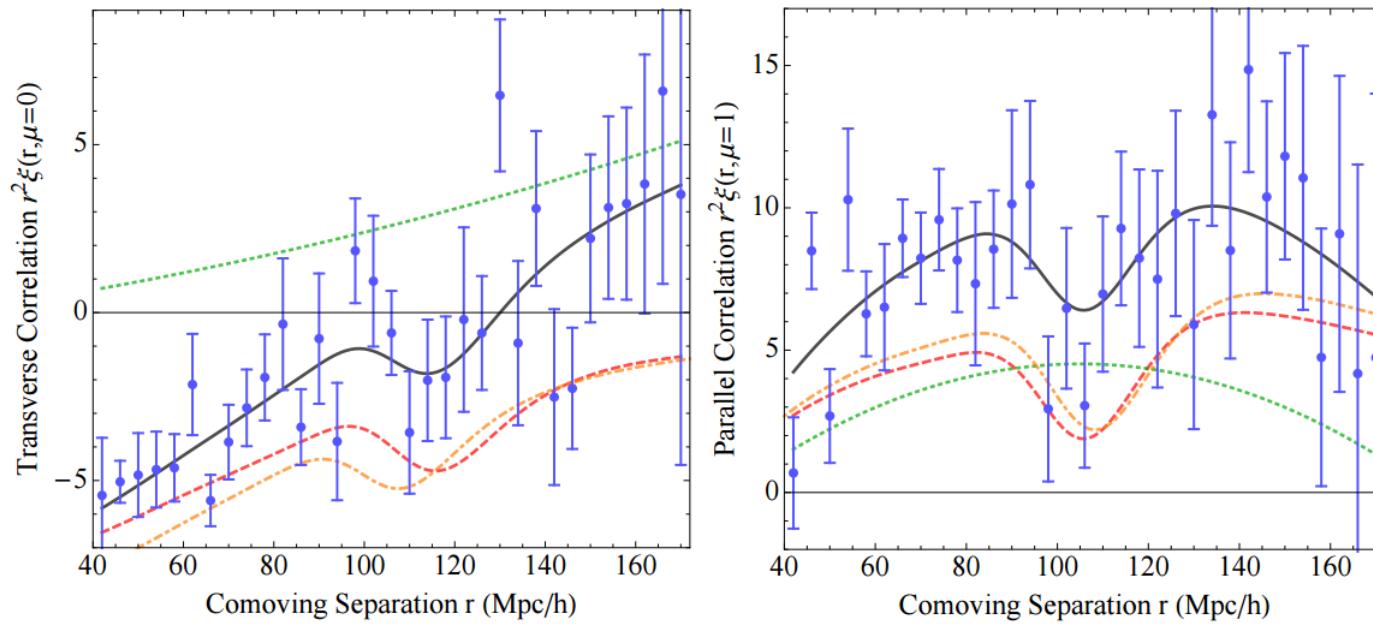
# The BAO feature in the Ly-A forest



~2% distance measurements at  $z \sim 2.5$

Delubac et al 2014

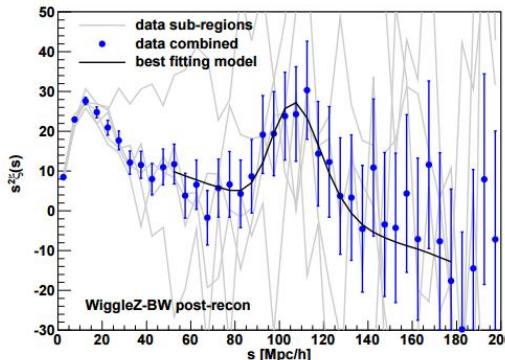
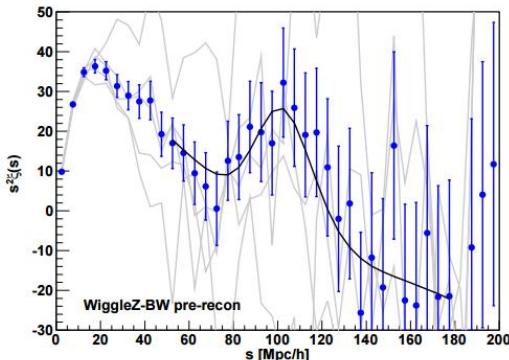
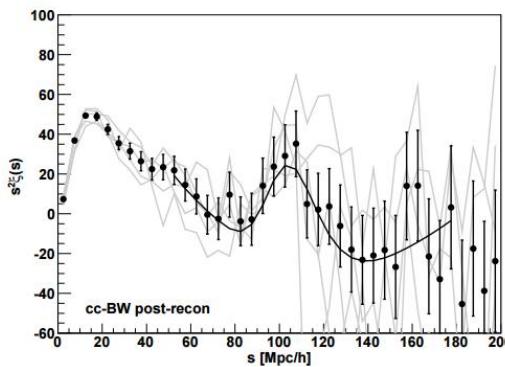
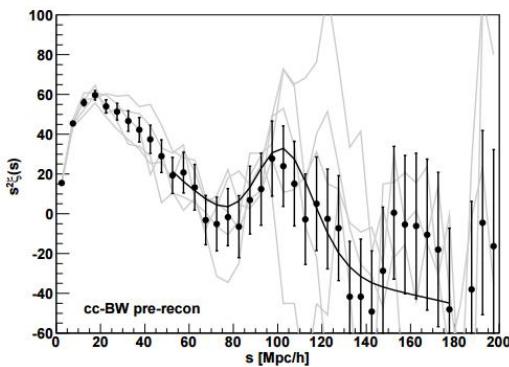
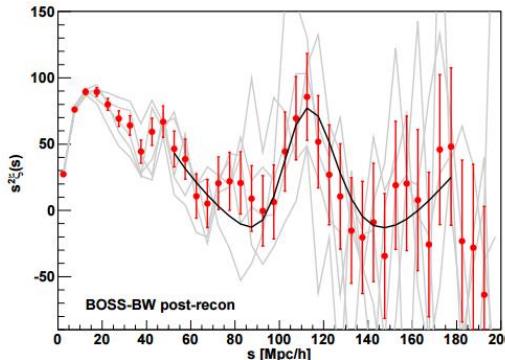
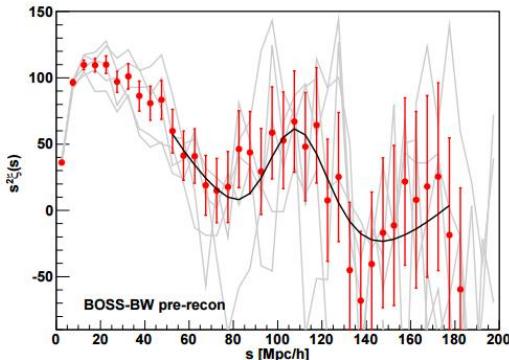
# BAO in cross-correlations



Cross-correlate QSOs with the Lyman-alpha forest at the same redshift.  
 Similar constraining power to the Lyman-alpha forest autocorrelation

Analysis	Probe	Data Release	$\alpha$	$\alpha_{\parallel}$	$\alpha_{\perp}$
Busca_2013	Auto	DR9	$1.01 \pm 0.03$	-	-
Slosar_2013	Auto	DR9	$0.98 \pm 0.020$	$0.99 \pm 0.035$	$0.98 \pm 0.070$
This work	Cross	DR10	$1.00 \pm 0.027$	$1.06 \pm 0.038$	$0.91 \pm 0.041$
This work	Cross	DR11	$0.99 \pm 0.022$	$1.04 \pm 0.034$	$0.93 \pm 0.036$
Busca_2013	Auto	to DR11	$\pm 0.019$	-	-
Slosar_2013	Auto	to DR11	$\pm 0.013$	$\pm 0.022$	$\pm 0.046$

# BAO in cross-correlations



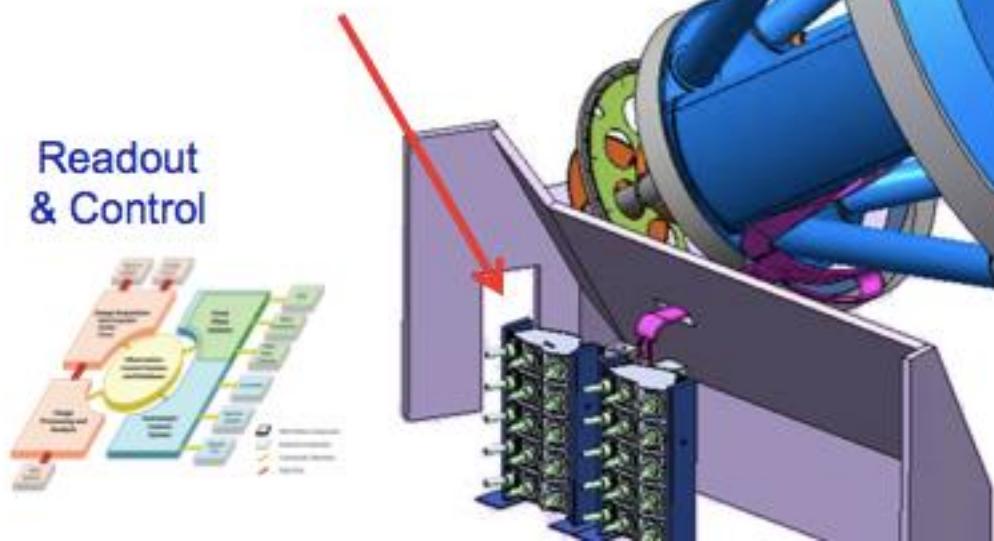
Cross-correlate WiggleZ and BOSS

Test for systematics in the distance measurements, reconstruction

Tests for effects due to galaxy bias...

# DESI

- 5000 fibers in robotic actuators
- 10 fiber cable bundles
- 3.2 deg. field of view optics
- 10 spectrographs

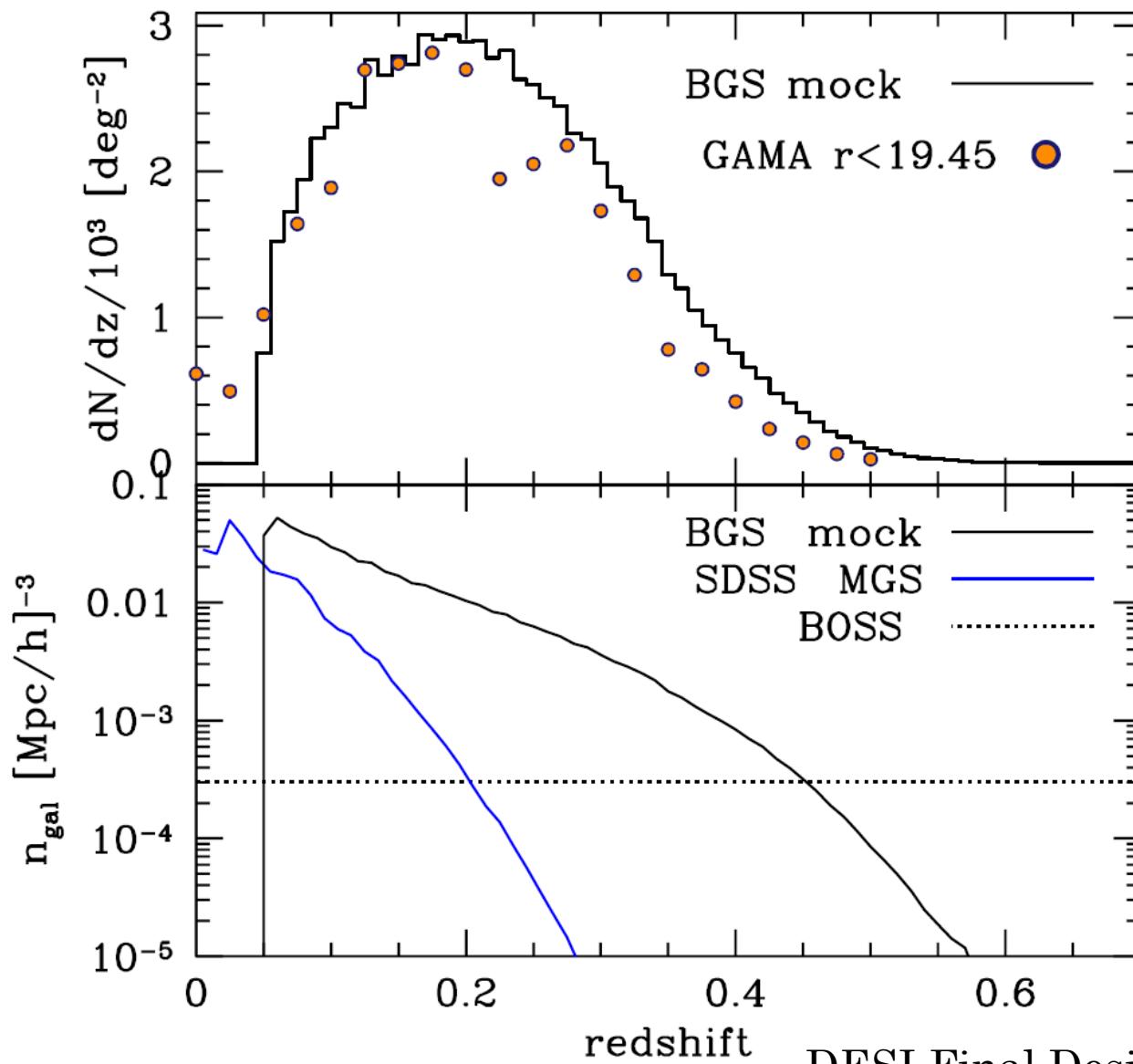


**Mayall 4m  
Telescope  
Kitt Peak  
Tucson, AZ**

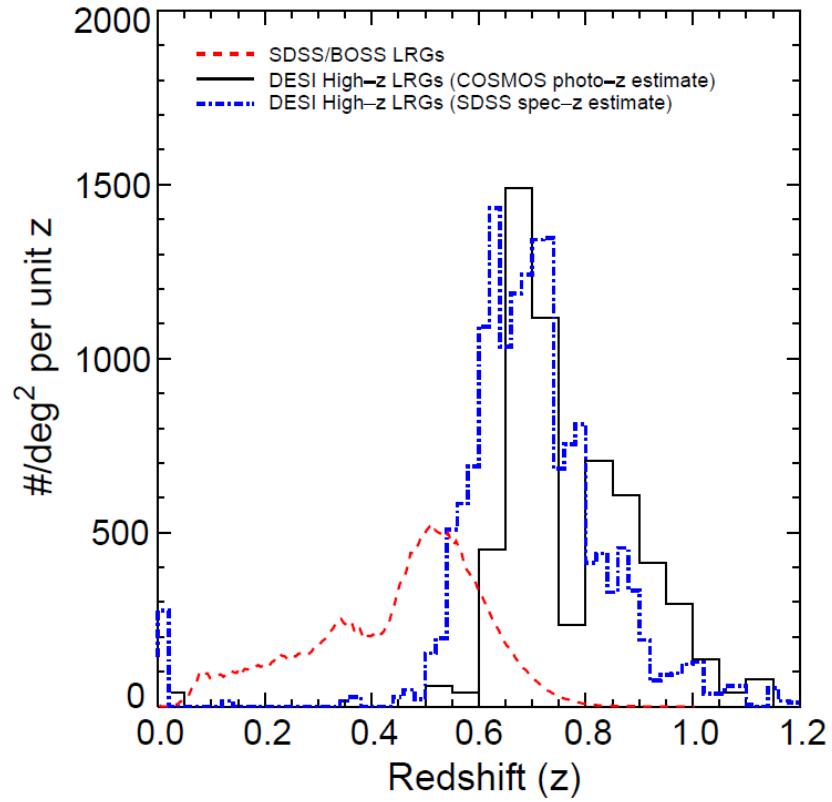
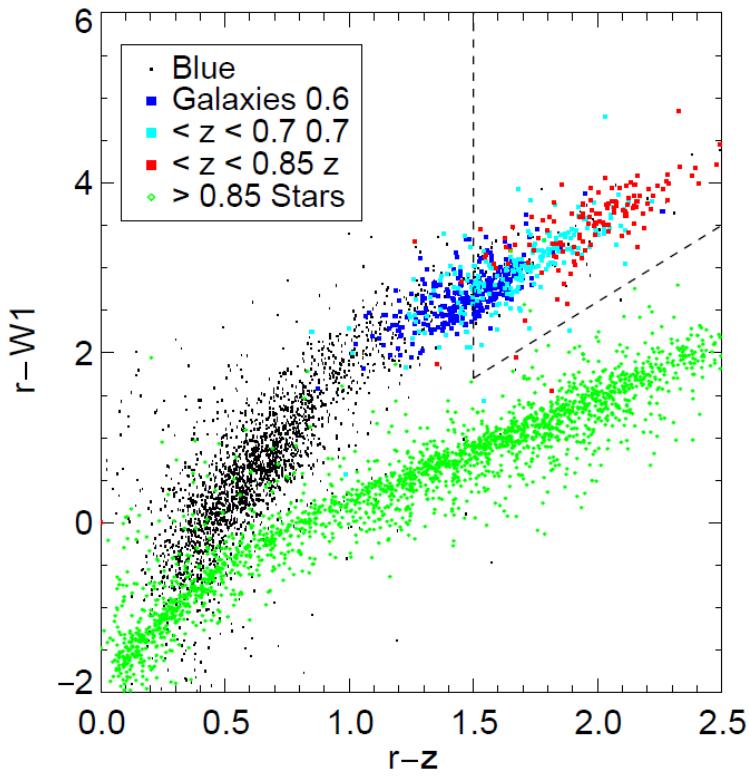
# The DESI Survey

- 2019-2024
- 14000 sq. deg.
- Tracers
  - Bright galaxy survey ( $r < 19.5$ ,  $z < 0.4$ )
  - Red galaxies ( $z < 1$ )
  - Emission line galaxies ( $z < 1.7$ )
  - Tracer QSOs ( $1 < z < 3$ )
  - Lyman-alpha forest
  - **Designed to have multiple possible cross correlations**
- Imaging
  - DECam data ( $\text{dec} < 30$ ) : 9000 sq.deg
  - Bok, Mosaic data ( $\text{dec} > 30$ )
  - WISE data

# The bright galaxy sample

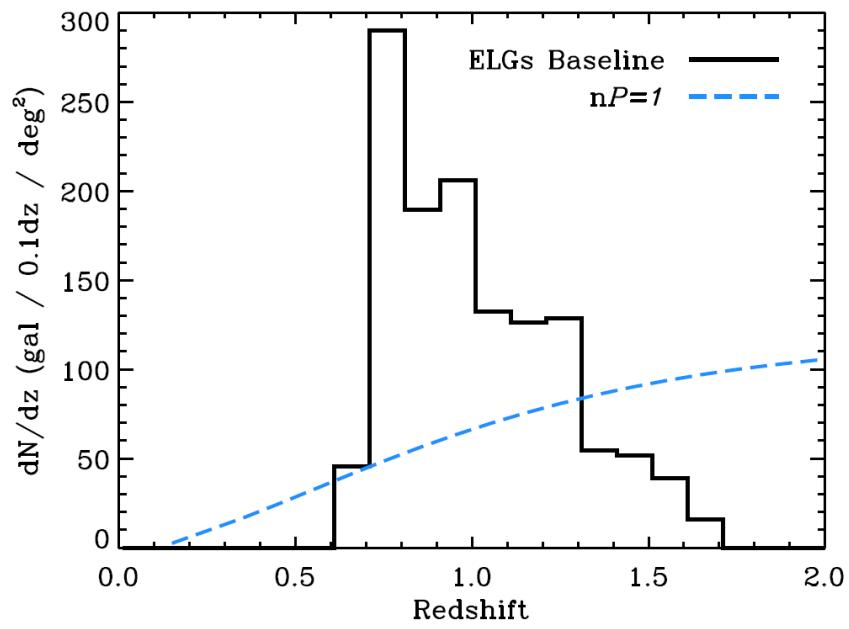
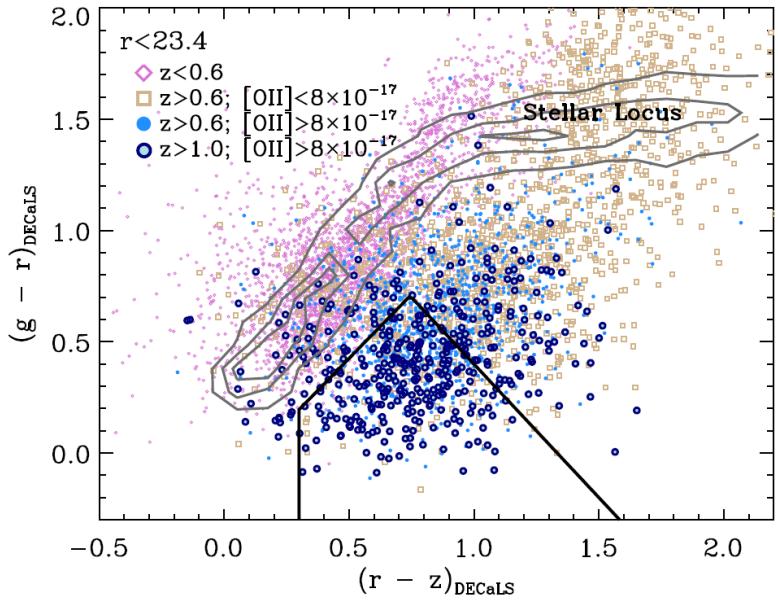


# Luminous Red Galaxies



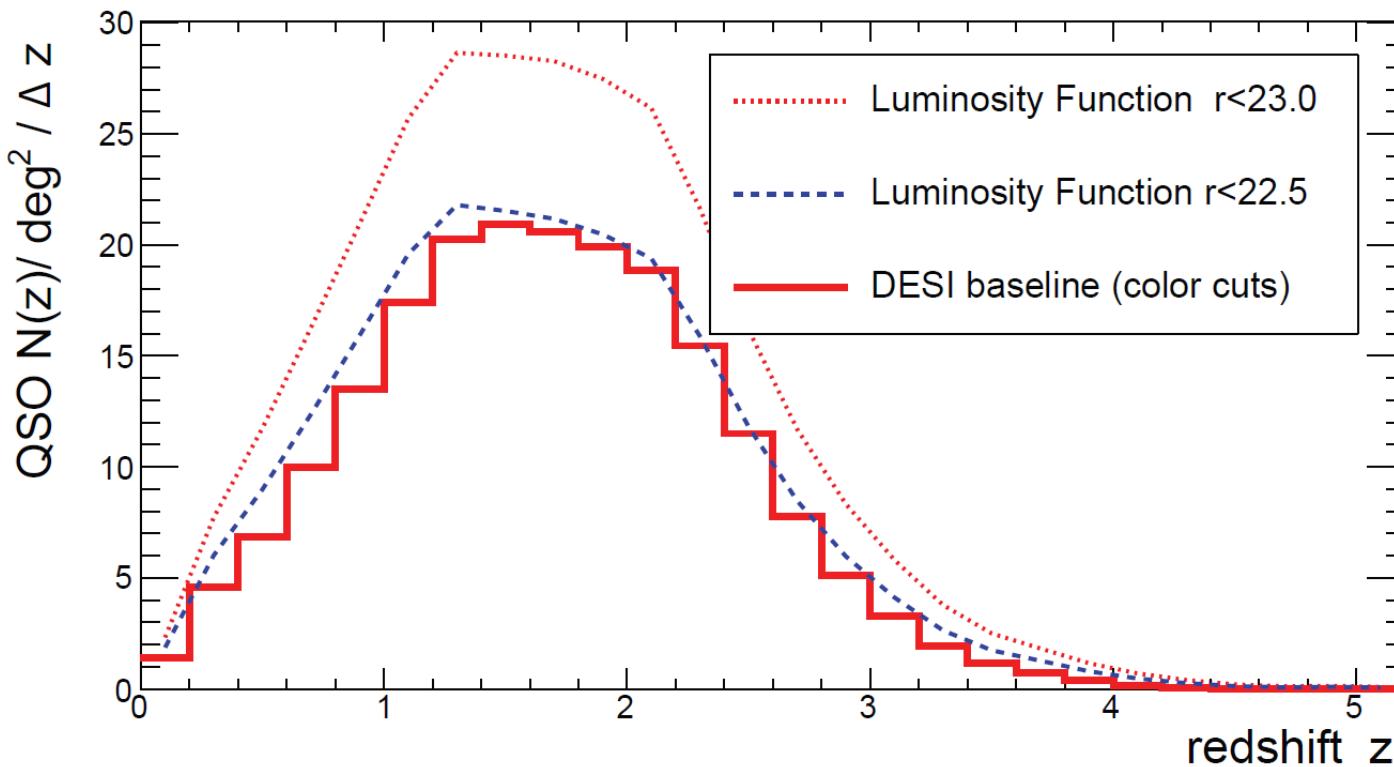
Conceptually very similar to  
the SDSS/BOSS LRGs, higher  
redshift

# Emission line galaxies



# Quasars

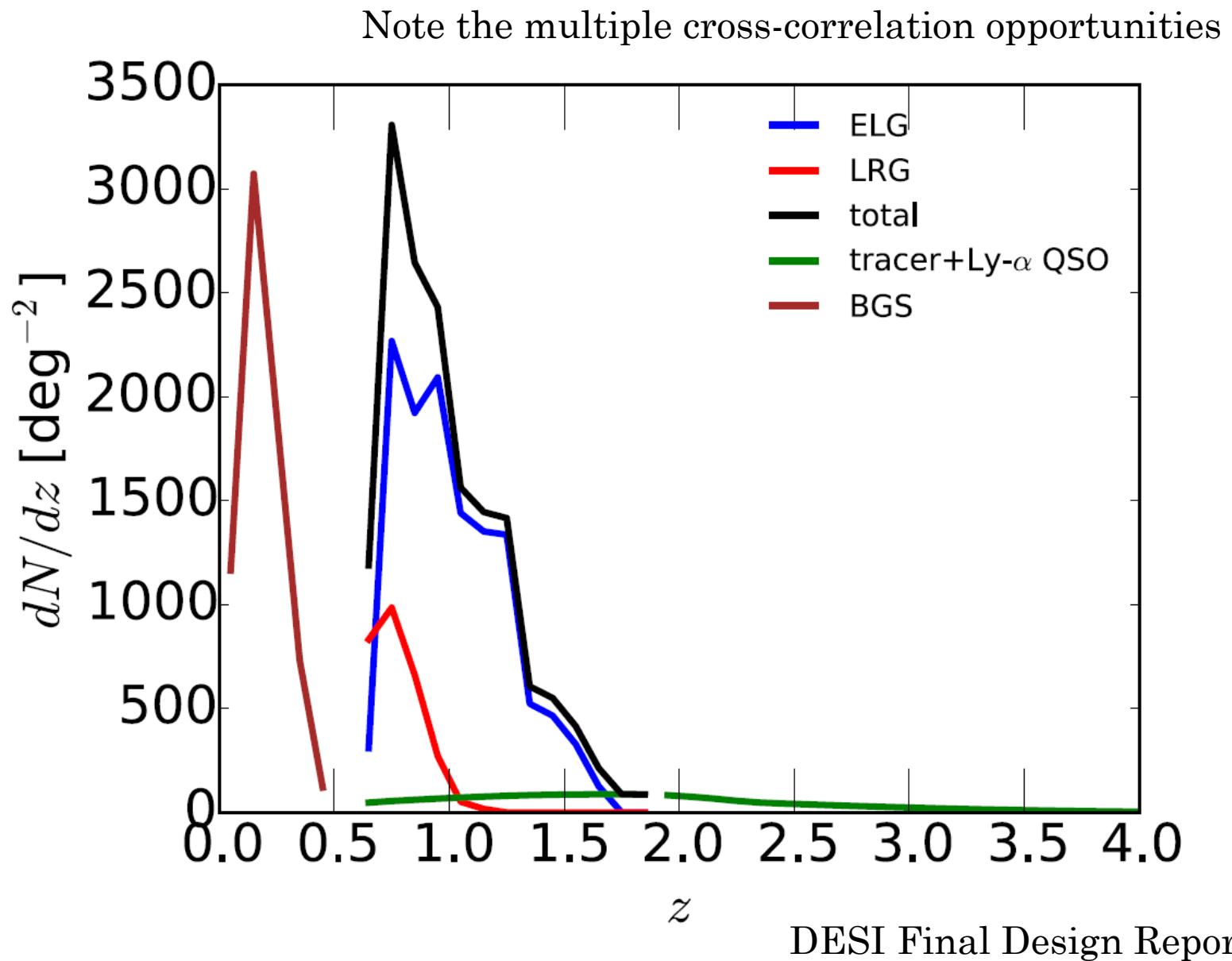
24 May 2016



Play a dual role : tracers of large scale structure and backlights for the Lyman-alpha forest

CCS 2016

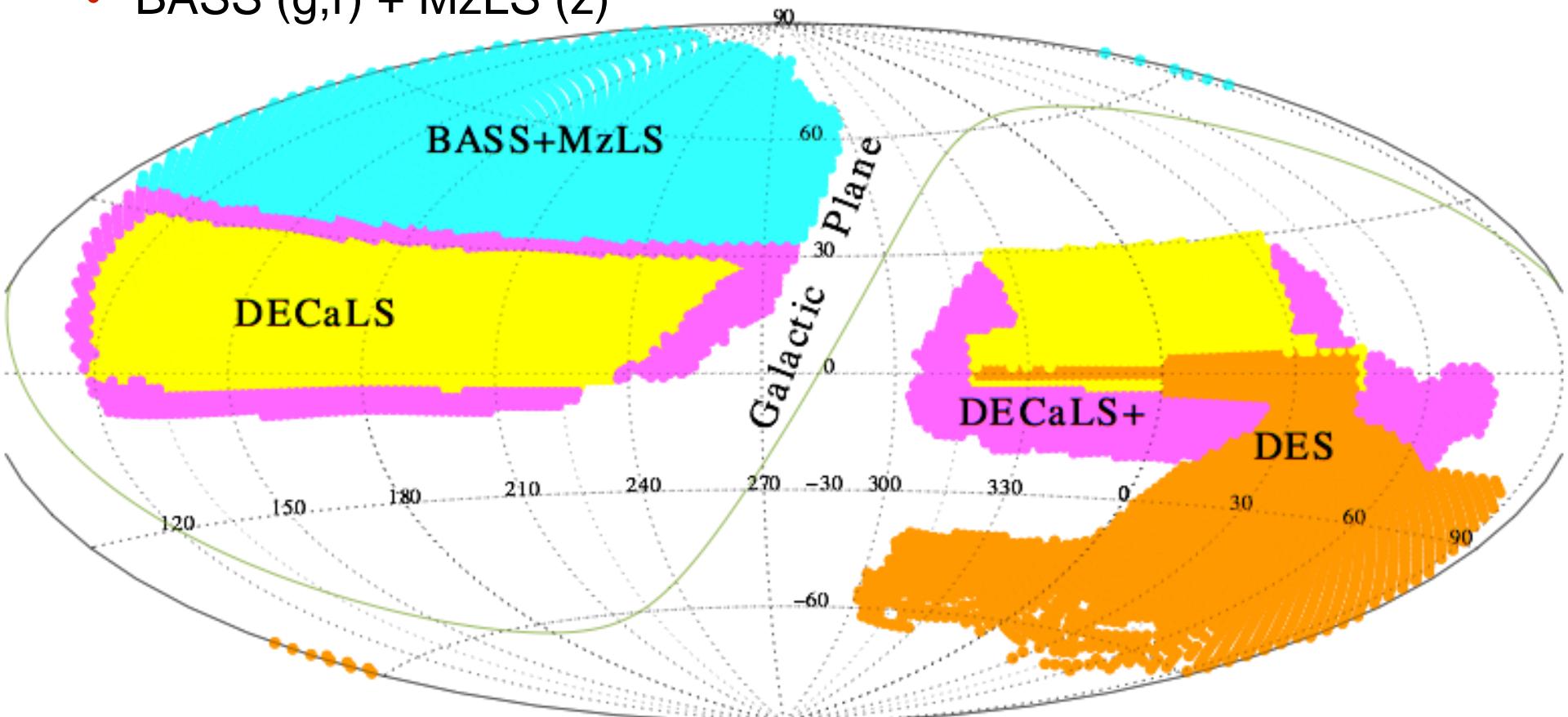
# DESI tracers in redshift



# DESI science collaboration leading imaging surveys for DESI target selection

Three new optical surveys covering 14,000 deg<sup>2</sup> DESI footprint

- DECaLS (g,r,z)
- BASS (g,r) + MzLS (z)



Dark Energy Spectroscopic Instrument  
U.S. Department of Energy Office of Science  
Lawrence Berkeley National Laboratory

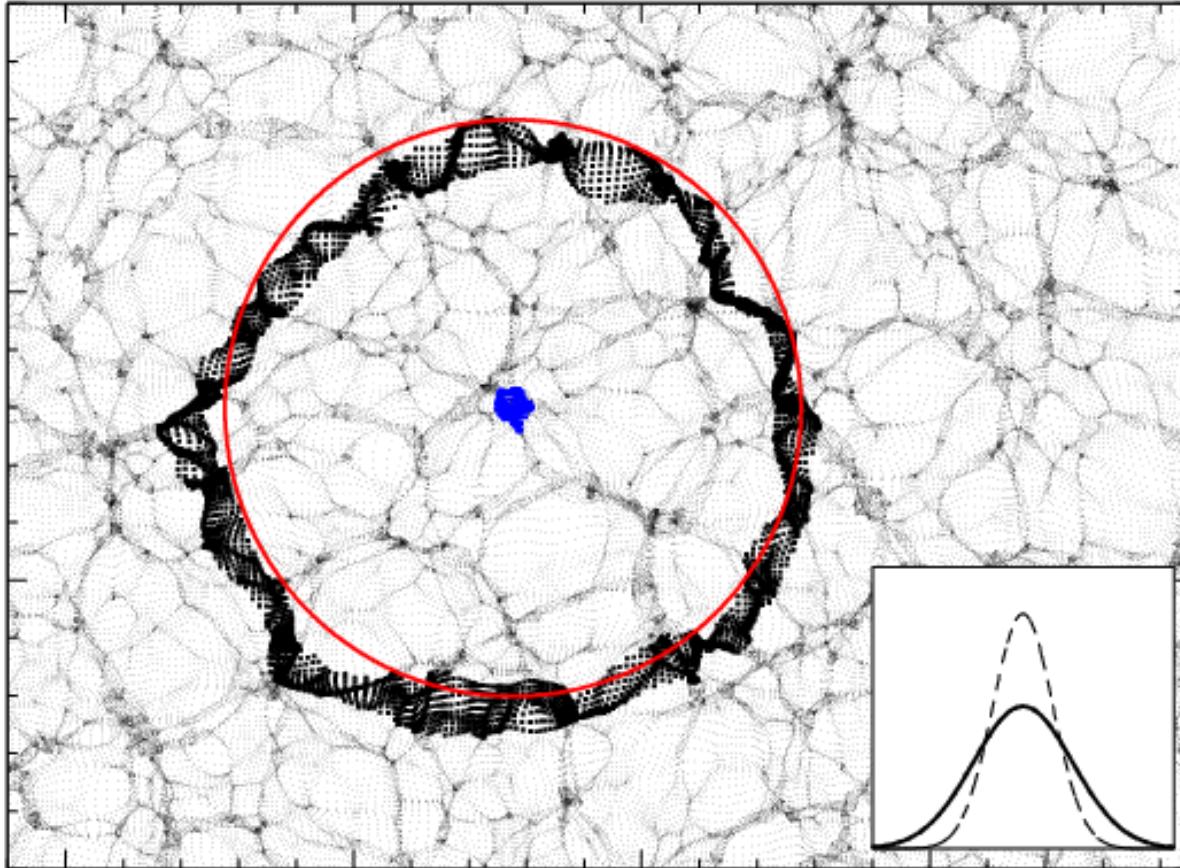
D. Schlegel, A Myers - BO1.2  
May 2016 DOE Review for CD-3

# Reconstruction and “Cross-correlation”

J. Cohn, M. White, T.C.Chang, G. Holder, NP, O. Dore,  
1511.07377

# Nonlinear evolution smooths out the BAO feature

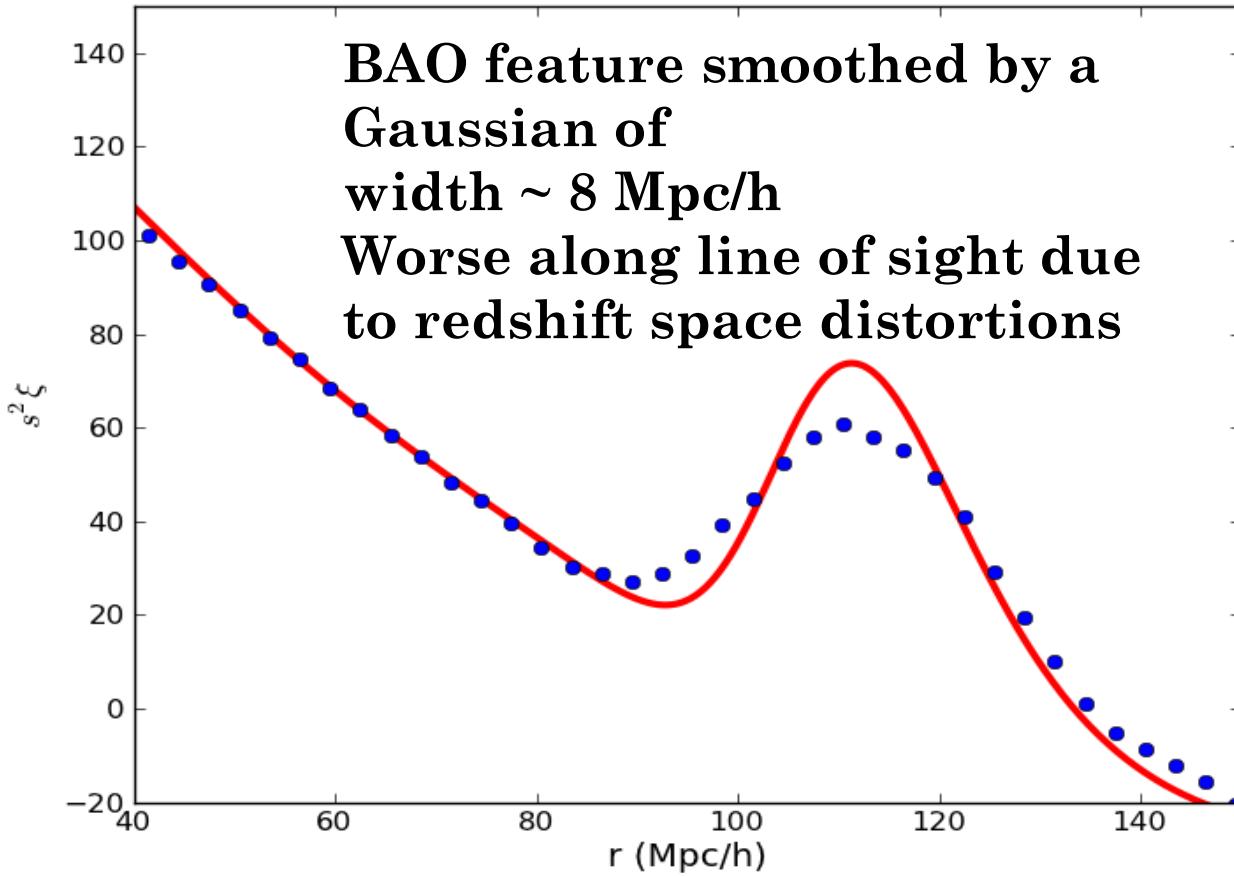
Primary contribution are large-scale flows



See Crocce & Scoccimarro 2007, NP & White 2009, NP,  
White, Cohn 2009, Noh, White, NP 2010, Sherwin &  
Zaldarriaga 2012

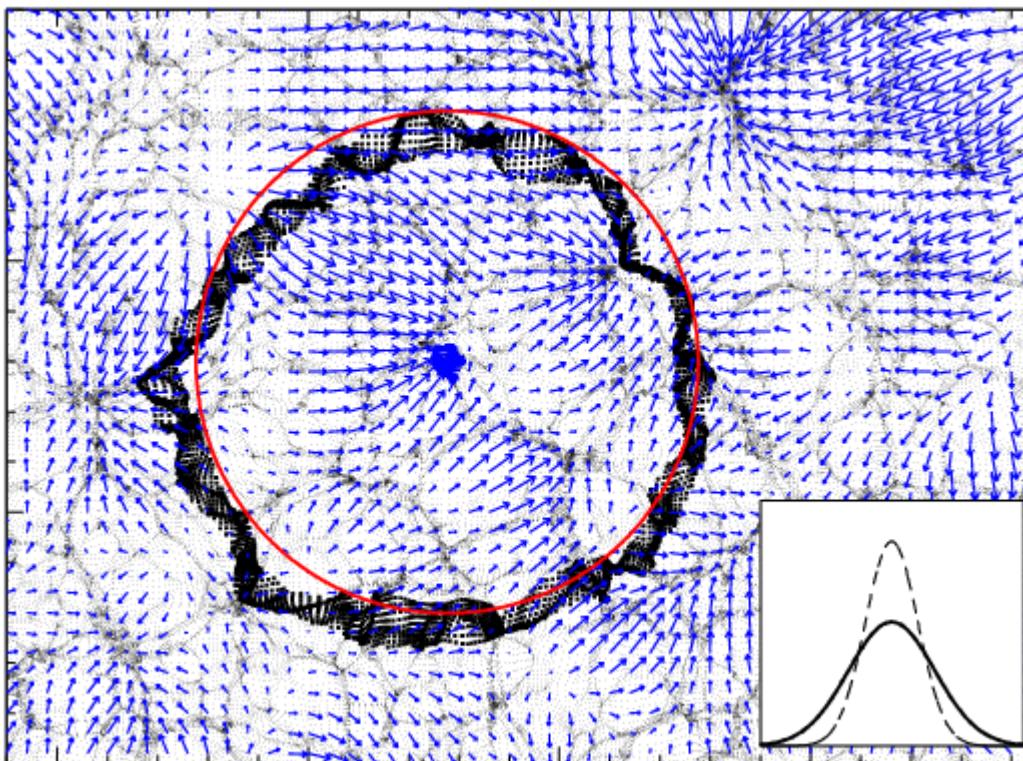
# Nonlinear evolution

24 May 2016

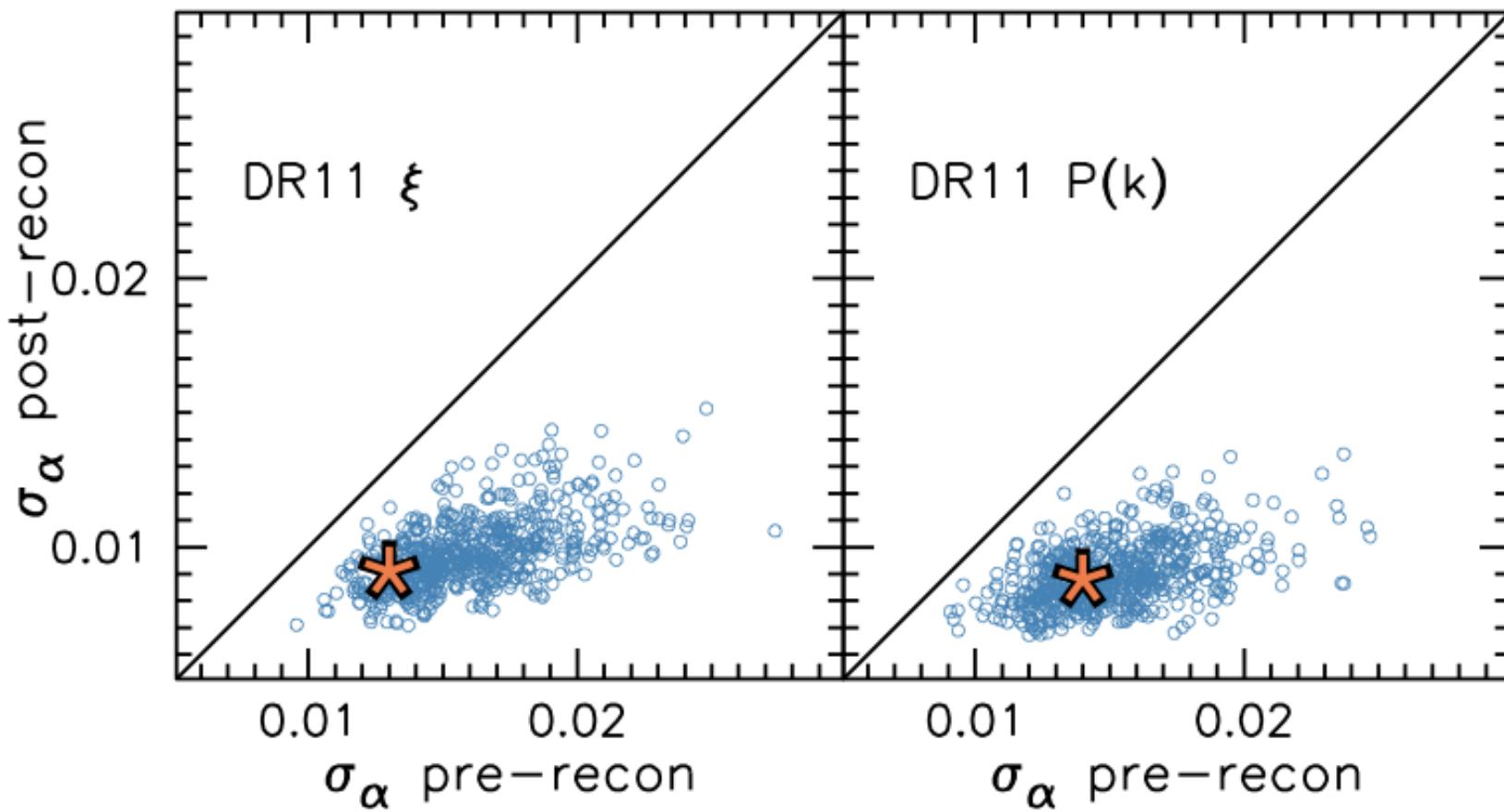


CCS 2016

# Reconstruction



# Improvements with BAO reconstruction



Anderson et al, 2013

# Understanding reconstruction

- A number of different explanations : Lagrangian PT, separate Universe (NP, Cohn, White, 2009; Sherwin, Zaldarriaga 2012)
- Follow an Eulerian treatment here (Schmittfull et al, 2015)

$$\delta(\mathbf{x}, \eta - \Delta\eta) \approx \delta(\mathbf{x}, \eta) - \Delta\eta \partial_\eta \delta(\mathbf{x}, \eta) \equiv \delta_{\text{rec}}(\mathbf{x}),$$

$$\partial_\eta \delta(\mathbf{x}, \eta) = -\nabla \cdot \mathbf{v}(\mathbf{x}, \eta) - \mathbf{v}(\mathbf{x}, \eta) \cdot \nabla \delta(\mathbf{x}, \eta) - \delta(\mathbf{x}, \eta) \nabla \cdot \mathbf{v}(\mathbf{x}, \eta).$$

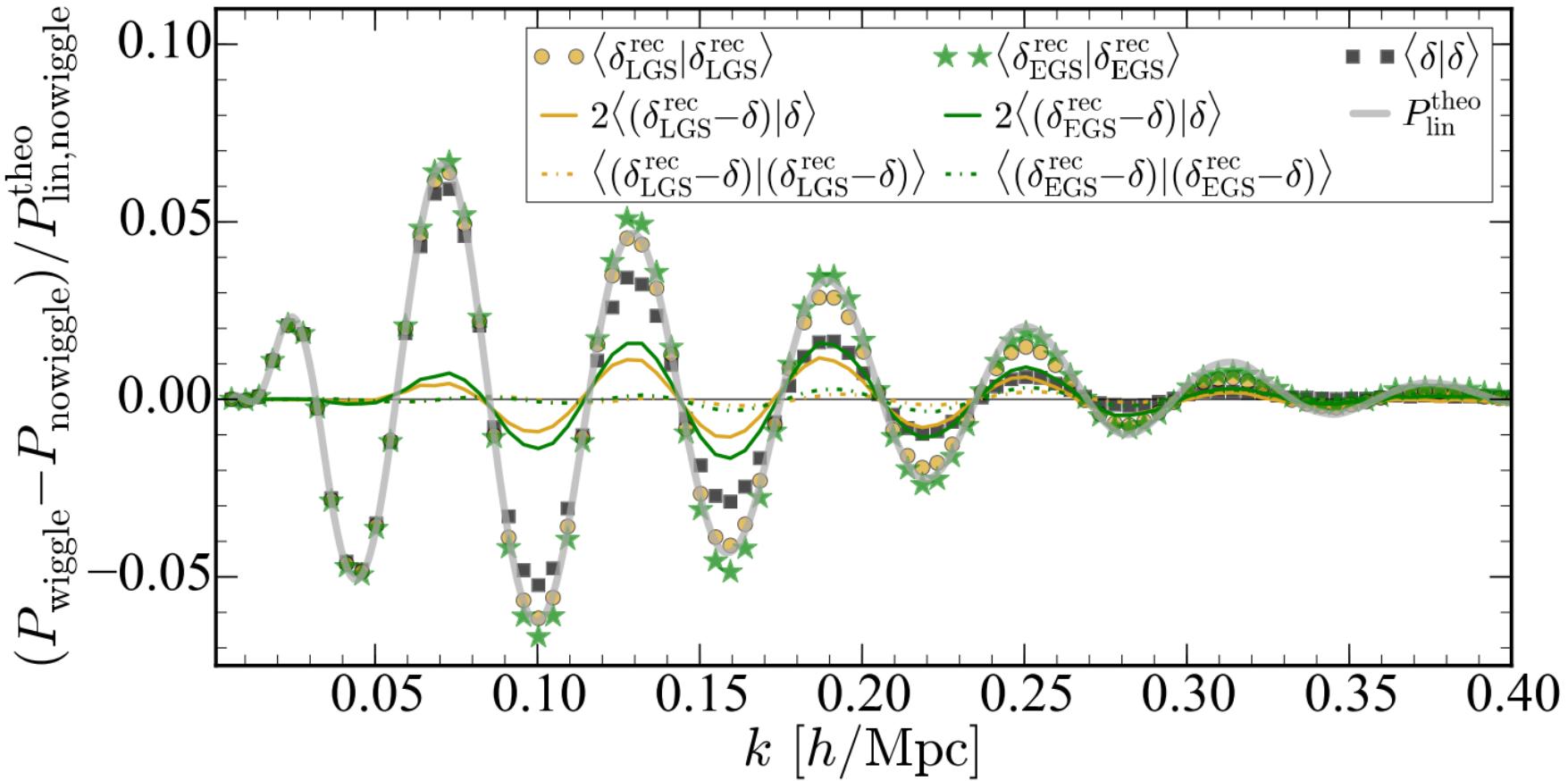
$$\delta_{\text{EGS}}^{\text{rec}}(\mathbf{x}) = \delta(\mathbf{x}, \eta) - \underbrace{\mathbf{s}(\mathbf{x}, \eta) \cdot \nabla \delta(\mathbf{x}, \eta)}_{\text{shift}} - \underbrace{\delta(\mathbf{x}, \eta) \delta_R(\mathbf{x}, \eta)}_{\text{growth}},$$

Compare to nonlinear growth

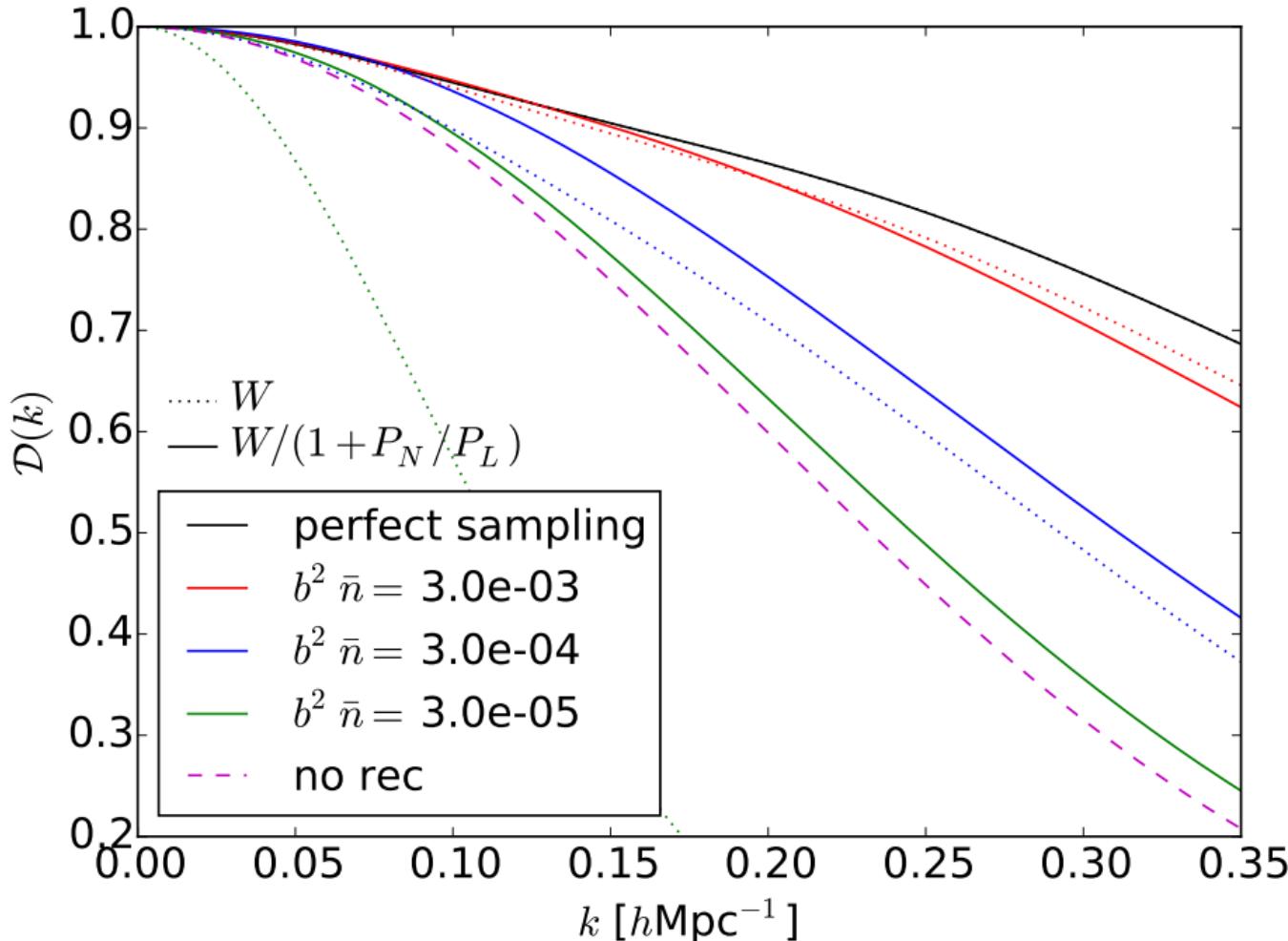
$$\delta^{(2)}(\mathbf{x}) = \underbrace{\frac{17}{21} \delta_0^2(\mathbf{x})}_{\text{growth}} - \underbrace{\Psi_0(\mathbf{x}) \cdot \nabla \delta_0(\mathbf{x})}_{\text{shift}} + \underbrace{\frac{4}{21} K_0^2(\mathbf{x})}_{\text{tidal}}.$$

# Reconstruction goes beyond 2-pt

24 May 2016



# Damping BAO



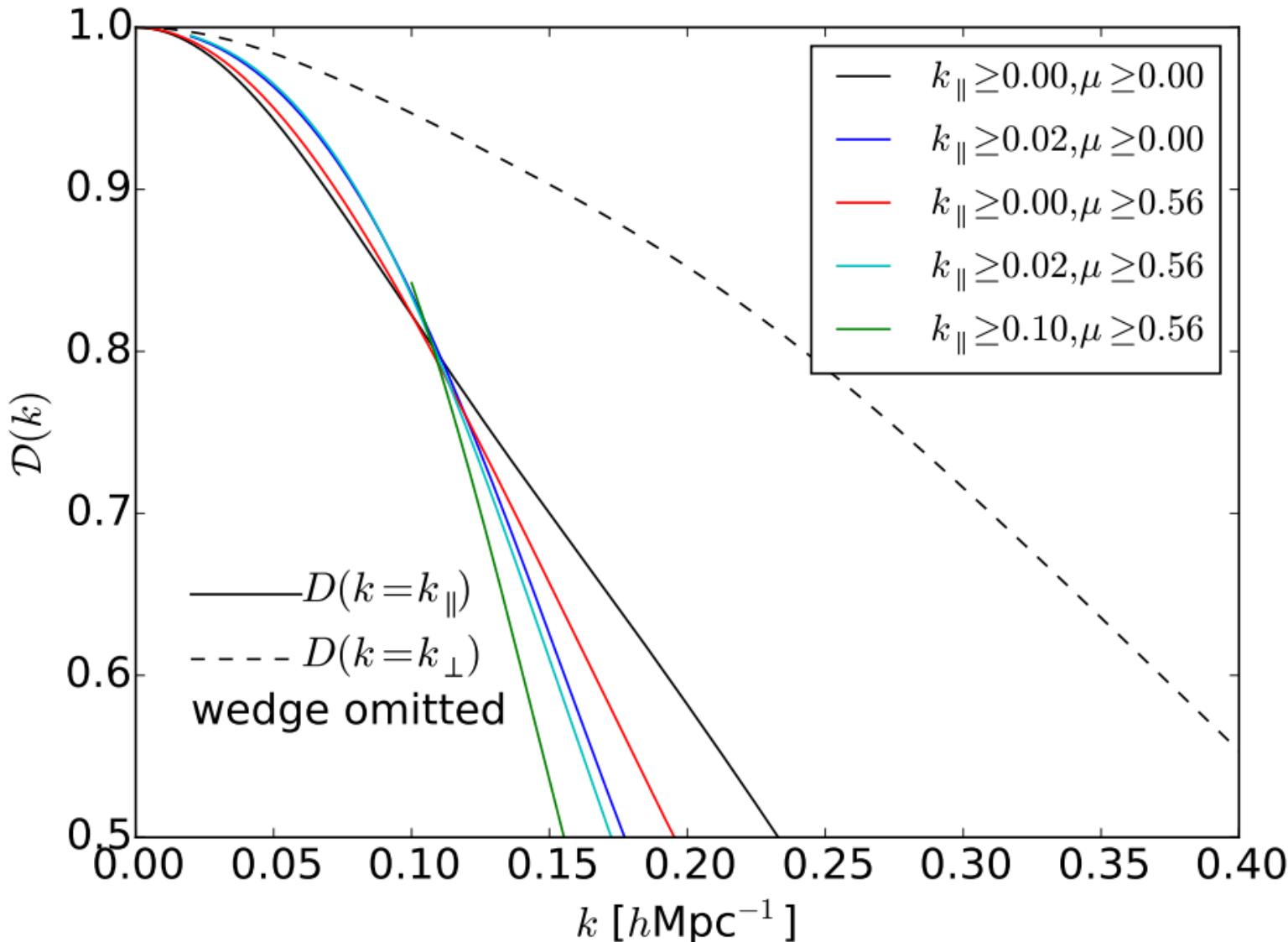
$$P_{\text{rec}}(k, \mu) = (b + f\mu^2)^2 \mathcal{D}(\mathbf{k}) P_L(k) + \dots$$

Cohn et al, 2016

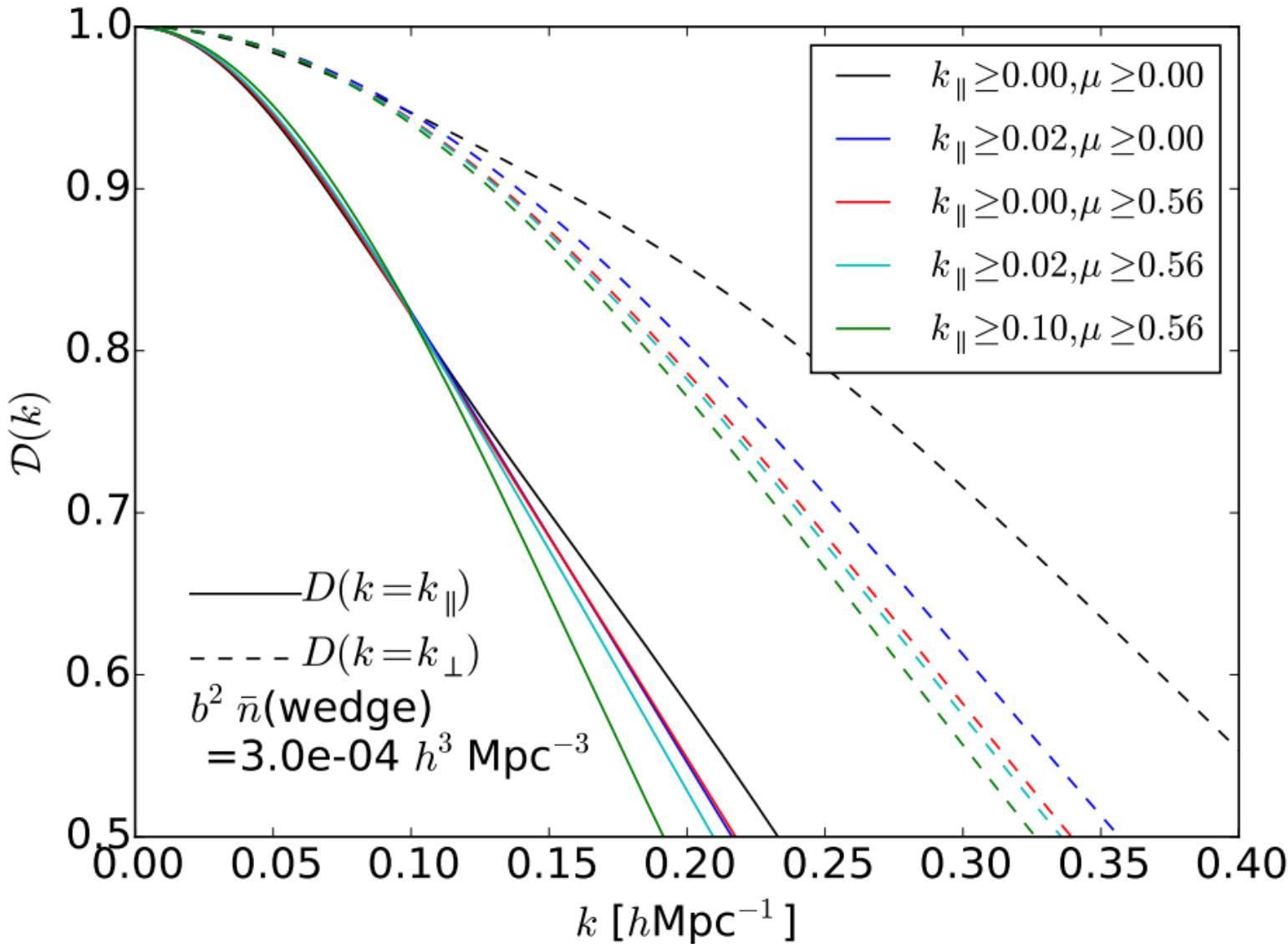
# What has this got to do with cross-correlations?

- (I'm being imprecise with "correlation" here)
- Imagine a survey with missing modes (eg. due to foreground removal, as with a 21cm)
  - If linear, modes are lost
  - If nonlinear, maybe can be reconstructed by using mode-coupling....
  - Can we do something simple – like filling in modes from another survey?
- Reconstruction uses long wavelength modes
  - These are missing in a 21cm survey
  - Limit reconstruction (Cohn et al, 2015, Seo & Hirata 2015)
  - Maybe fill in with a sparse sample

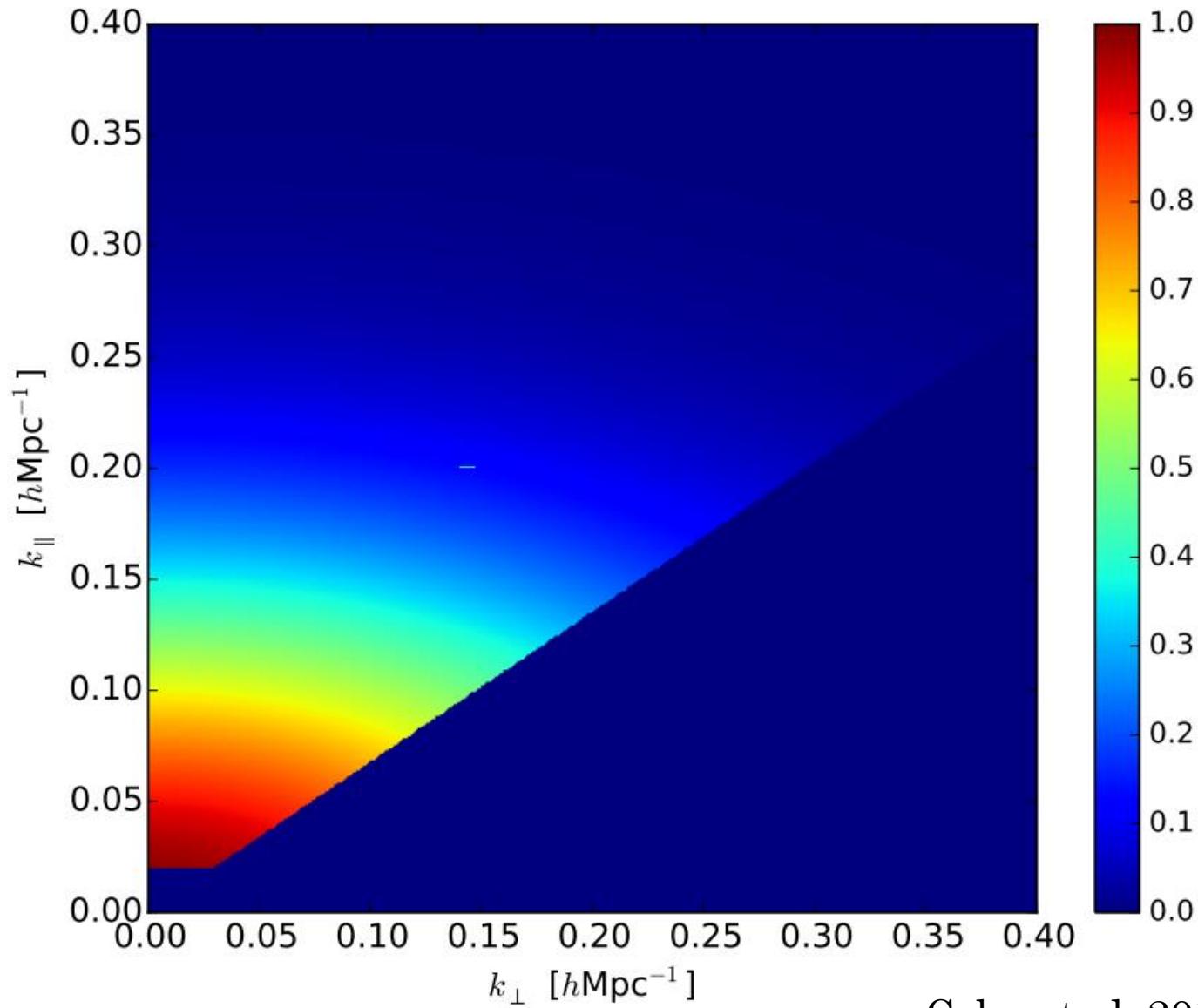
# The loss of modes limits reconstruction



# Filling in missing modes improves reconstruction

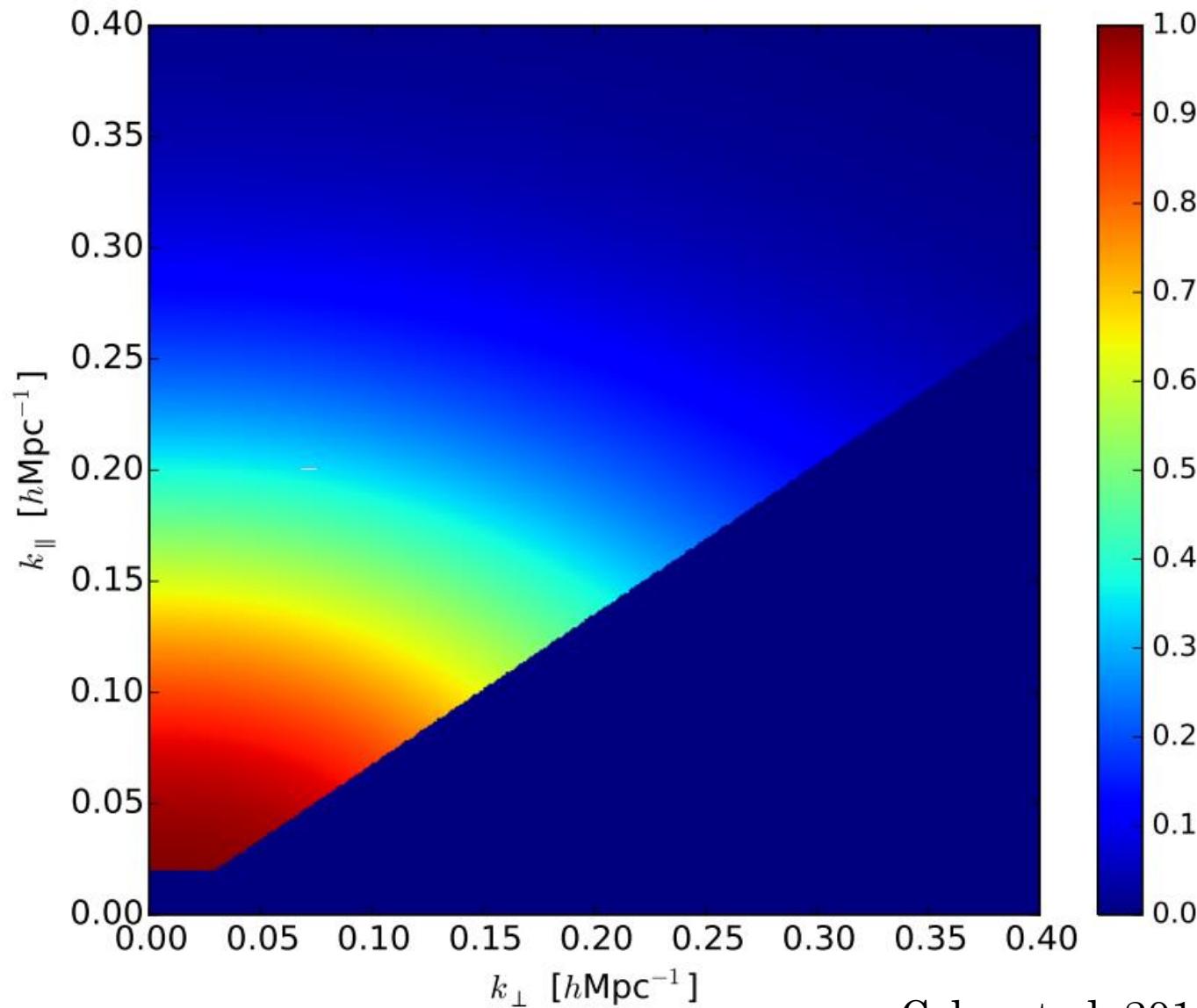


# Damping of the BAO, with lost modes



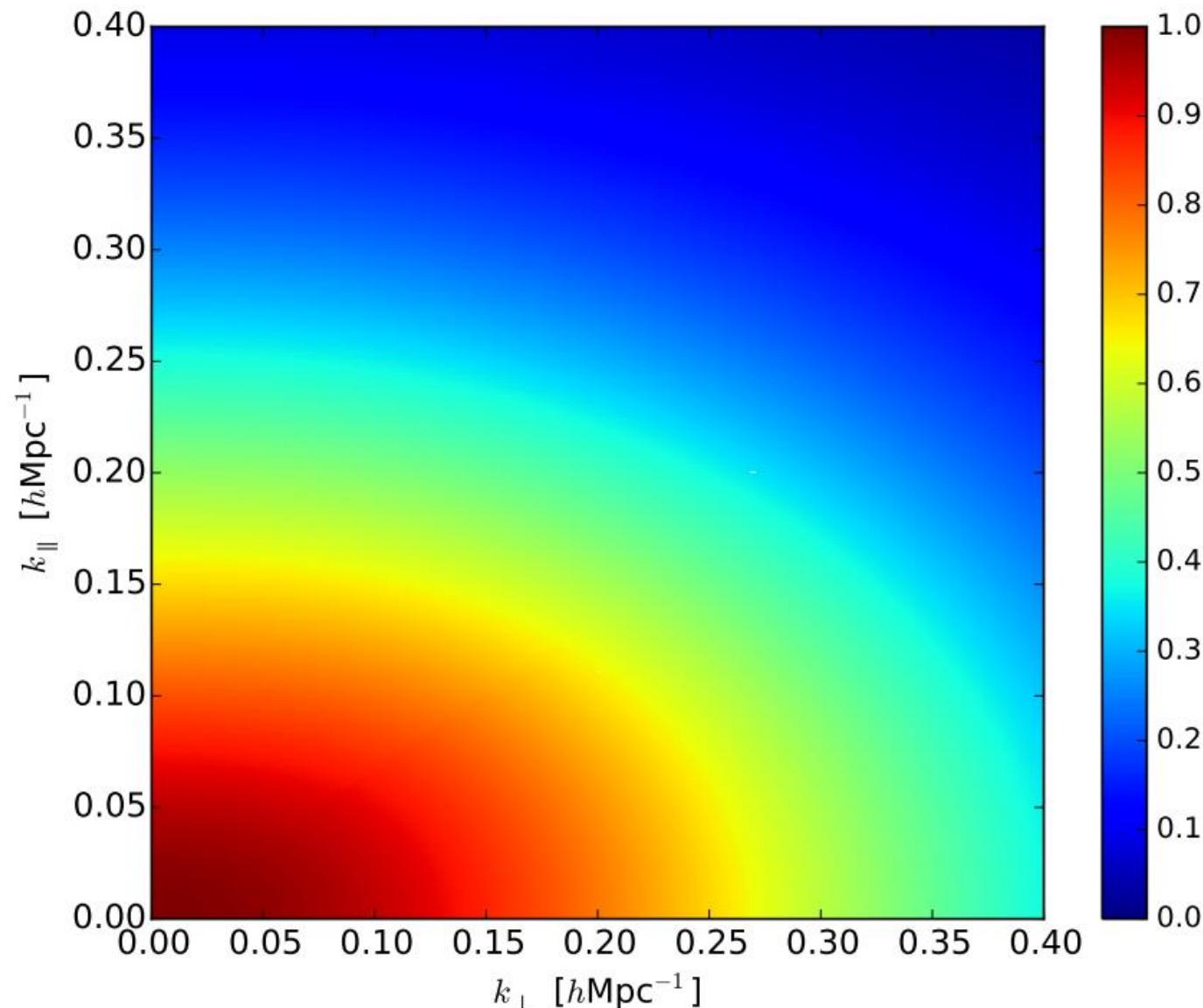
Cohn et al, 2016

# Reconstruction with lost modes



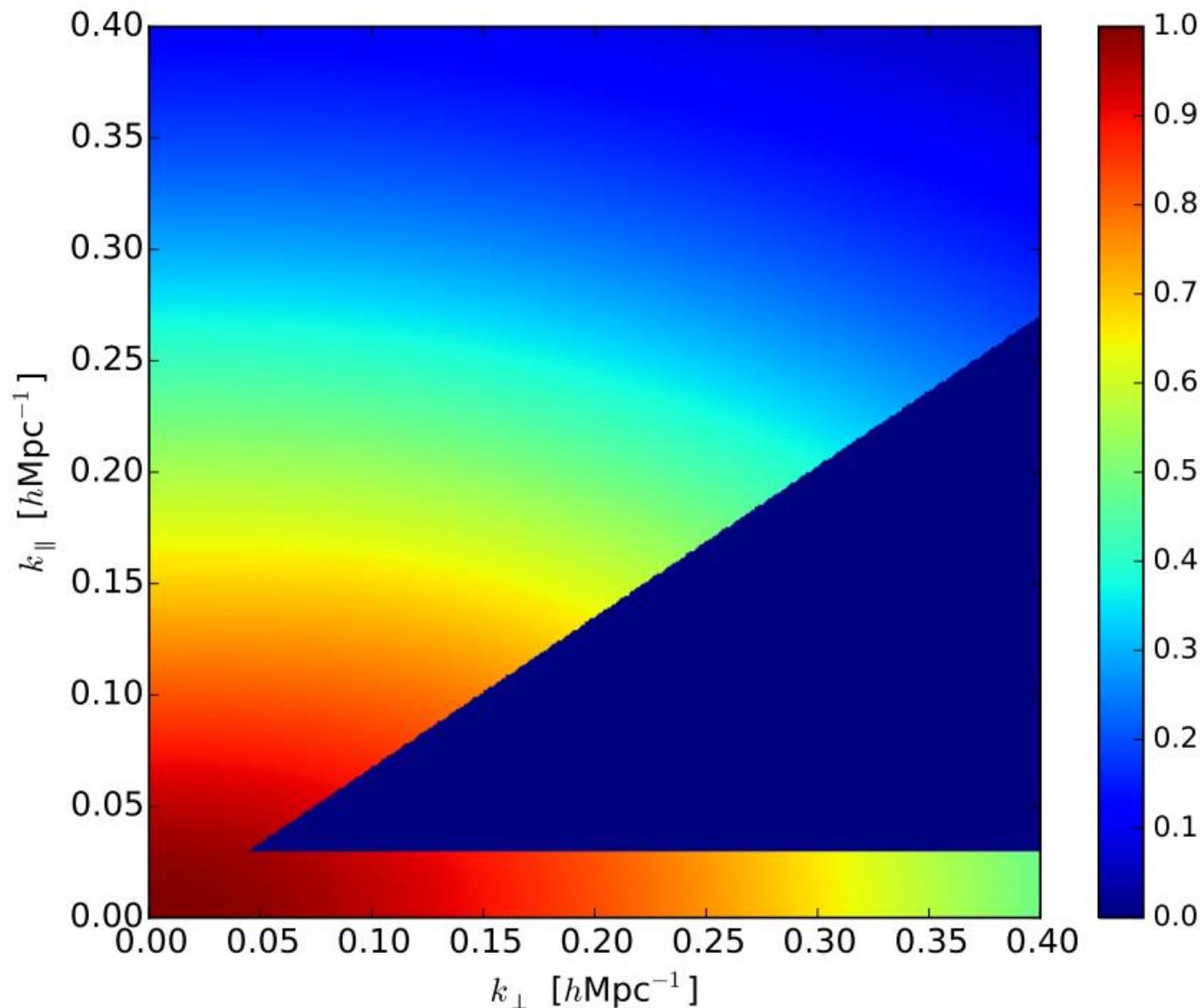
Cohn et al, 2016

# Filling in with an ELG survey



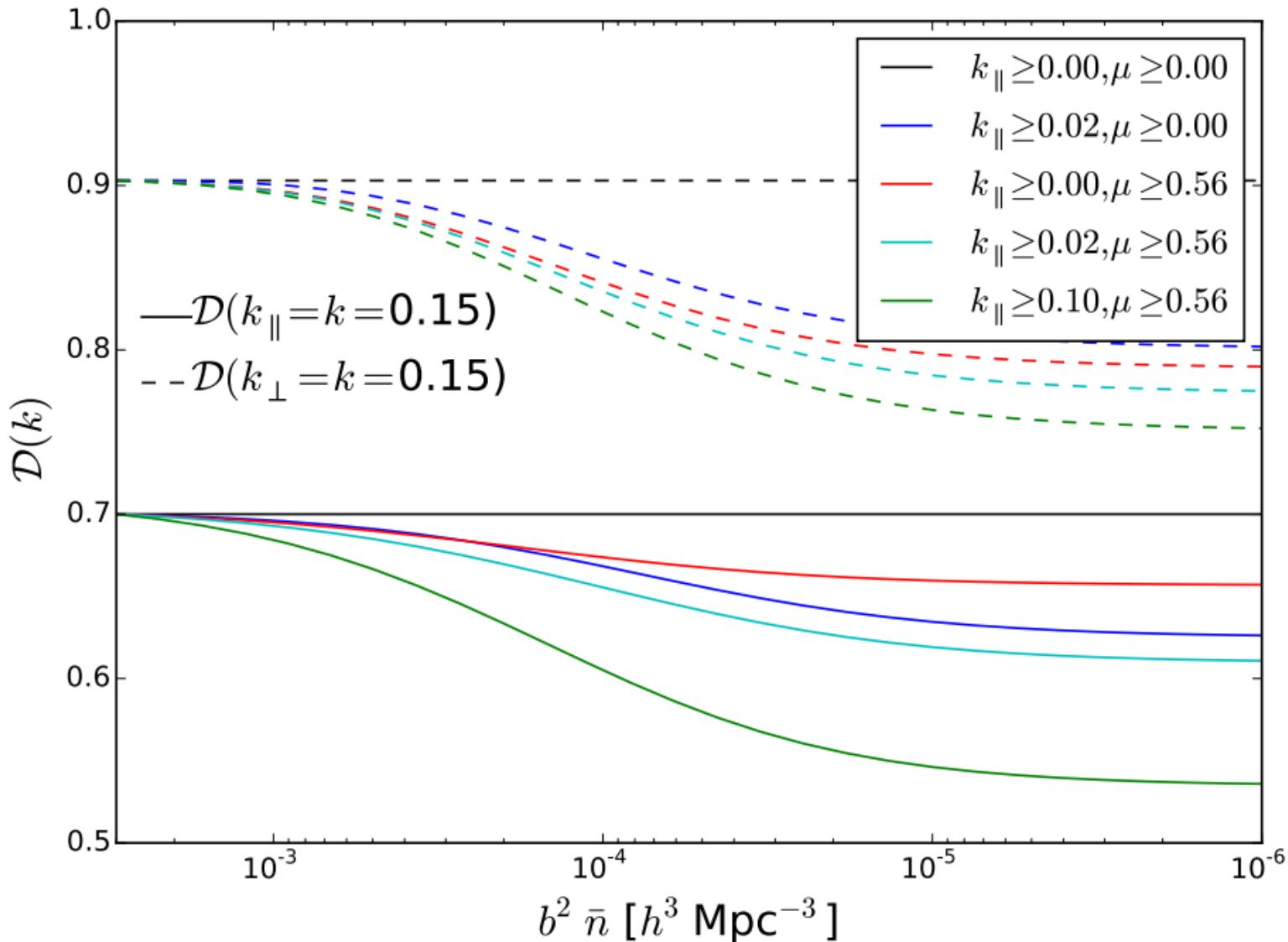
Cohn et al, 2016

# Filling in with a photometric survey



Cohn et al, 2016

# Dependence on number density/bias



# Conclusions

- DESI
  - First science data in 2019
- Lots of cross-correlation opportunities